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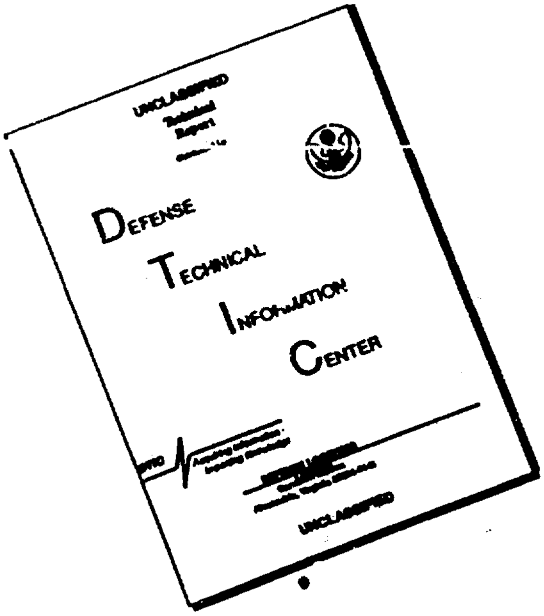

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A SIZE-SEPARATION COLLECTOR FOR SAMPLING AEROSOLS FROM CURVILINEAR FLOW

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In this report a description is given of a collector for sampling aerosol particles from a curvilinear flow and a method is suggested for analyzing the samples and obtaining distribution statistics. It is shown that the collector can be used to analyze aerosols with a minimum particle size 0.7-0.8μ. The results of determination of distribution parameters agree with microphotographic data.

I. Study of the microstructure of aerosols is needed in solving many problems related to the transparency of the atmosphere and prediction of its optical and physical properties. Existing methods of studying dispersion and the countable aerosol concentration, with a few exceptions, represent an obstacle for sampling and settling of the aerosol sample and for analysis of the resulting photographs. These so-called flow methods are most widely used in studying the structure of clouds, fogs, and condensation nuclei. A detailed validation of a flow method and numerous experimental results obtained in the Elbrus Expedition of the Academy of Sciences USSR are found in the monograph by L. M. Levin [1]. Collectors devised in the Institute of Applied Geophysics can automatically collect 18 samples in 20-30 seconds, which affords the gathering of statistically valid data on the size-distribution function of drops. We must note that several shortcomings inherent in the flow method make difficult or altogether impossible the solution of several problems related to investigation of aerosol structure. We will point out some of them.

1. Analysis of microphotographs is a fatiguing and laborious process. Autocorrelational analysis of negatives somewhat facilitates the obtaining of distribution parameters, however it substantially distorts the final results.

2. Owing to the inertia of aerosol particles the distribution function in collecting a sample can be significantly skewed. Hence it is necessary to compute the capture coefficient for each small region of the collector plate. Determining the capture coefficient experimentally is difficult, therefore a certain indeterminacy arises in estimating the error of calculation.

3. The minimum size of captured particles is determined by the flow rate of the aerosol and by the dimensions of the collector plate. In the experiments of the Elbrus expedition d_{min} was $4\,\mu$. Consequently, with the use of such collectors the investigation of mists and fine-drop clouds with median diameters $1.5 - 2\,\mu$ observed in the vicinity of Tomsk became impossible.

4. In the photographing and analysis of the negatives, several factors are absent, causing by their absence variability in the distribution parameters [2].

Based on the foregoing, it is necessary to develop a method that surmounts the shortcomings of flow methods and satisfies the following conditions.

1) It is very convenient if when collecting a sample the particles are sorted by size by the device itself. In [3] a description is given of such an instrument -- the conifuge. It must be noted that at low and variable rates of sample suction into the conifuge the distribution function can be uncontrollably skewed. In [1] it is pointed out that to get satisfactory results with the use of flow methods it is necessary to have large intake amounts of air through the instrument; accordingly, for small-bore collectors it is necessary to sample from a steady flow moving at a high flow rate.

2) Sorting of particles in the instrument must substantially facilitate the obtaining of distribution parameters; the most laborious stages of result analysis must be excluded -- microphotographing and miscounting of drop images.

3) The obstacle on which the collection of samples is carried out must be flat and must ensure the collection of particles of the smallest diameters.

4) The collector must be automated and convenient in operation.

It appears to us possible to use as an obstacle the wall of a cylinder with axis equal to the radius of curvature R.

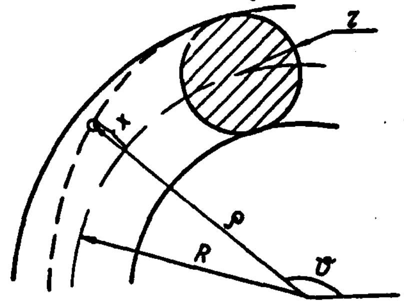
II. We will examine the trajectory of a spherical particle carried by an air flow into a cylinder with radius of cross-section r and with mean radius of curvature R (Figure 1). The equation of

its motion in vector form is written as follows [4]:

$$m\frac{d\bar{v}}{dt} = -6\pi\eta r(\bar{v}-\bar{u}) + \bar{F}, \qquad (1)$$

where $\bar{v}$ = vector of particle velocity, $\bar{u}$ = vector of velocity of medium, and $\bar{F}$ = vector of external force.

Figure 1.



By virtue of the fact that the inertial mean free path l for aerosol particles is small, in the curvilinear flow they will move perpendicular to the vector of the flow rate. In this case, movement with respect to the coordinate axes will be independent. In polar coordinates, in the case of the planar problem equation (1) will be of the form:

$$\left.\begin{aligned} m\frac{dv_\rho}{dt} &= -6\pi\eta r(v_\rho - u_\rho) + F_\rho \\ m\frac{dv_\theta}{dt} &= -6\pi\eta r(v_\theta - u_\theta) + F_\theta \end{aligned}\right\} . \qquad (2)$$

We will select as one variable x -- the distance of the particle from the tube axis. Taking into account the steady-state distribution of velocities in the cylinder,

$$\bar{u} = 2\bar{u}\left(1-\frac{x^2}{r^2}\right), \qquad (3)$$

where $\bar{u}$ = mean flow rate through the tube, equation (2) can be written in the following form:

$$\ddot{x} = A\dot{x} + B\frac{\left(1-\frac{x^2}{r^2}\right)^2}{R-x}, \qquad (4)$$

where $A = \frac{9\eta}{2\gamma Dd^2}$; D = density of droplet; d = diameter of droplet; $B = \frac{4\bar{u}^2}{m}$.

Let us assume that the form of the particular solution of (4) $x_1 = x_1(t)$ is known. The rate of particle settling under the effect of some external force will take on the form:

$$v = \tau f(x), \qquad (5)$$

where $\tau = \frac{\gamma d^2}{18}$, particle relaxation time. The solution of (5)

will be:

$$x_1 = \alpha d^2 F(t), \qquad (6)$$

where $\sigma = \frac{\gamma}{18\eta}$.

Neglecting change in the radius-vector of the particle ρ and the distribution of the field of flow rates in the cylinder, we obtain the following expression for the coordinate x of the particle:

$$x_2 = \alpha d^2 \Phi(t). \qquad (7)$$

x is not difficult to calculate from (7).

Let us designate by S_{x_1} the distance travelled by the particle from the beginning of the curvilinear flow to the point of encounter with the tube wall; S_{x_2} = this distance calculated from (7). The difference between S_{x_1} and S_{x_2} can be written in the following form:

$$\Delta S = \frac{\bar{u}}{r^2} d^2 (A_1 - B_1), \qquad (8)$$

where

$$A_1 = \int_0^{t_{x_2}} \bar{u} \left(1 - \frac{x^2_2(t)}{r^2}\right) dt,$$

$$B_1 = \int_0^{t_{x_1}} \bar{u} \left(1 - \frac{x^2_1(t)}{r^2}\right) dt.$$

Thus, since we have the value of x_2 calculated from (7) and the value of x_1 calculated from (6) for a specific diameter d_i, we can estimate the difference ΔS for a particle of any diameter, the movement of which is described by (1). Solution of (4) by numerical methods and its comparison with the solution of (7) has shown that S_i differs somewhat from S_2. Since we can use as the results of calculations of particle trajectories only for a qualitative interpretation of experimental results, we can use equation (7) for the calculations.

Equation (7) presupposes the settling of particles that is symmetrical with respect to the tube axis, therefore particles of the same diameter d_i will be distributed normally relative to a certain point on the tube wall at a distance S_i. The superpositioning of normal distributions evidently leads to the fact that over the section ΔS_i of the collector plate, the size distribution of particles will exhibit a certain skewness and will be close to the logarithmically normal distribution. If the relationship ld^2 = const is satisfied

for particles setting from the axial plane of the tube, then the following condition must be satisfied for median diameters of distributions calculated for each of the equal sections ΔS_i

$$l d_m = \text{const} .$$

This fact can be used for a simpler and more reliable graduating of the collector than is described in [5].

III. The collector for sampling aerosols and the curvilinear flow (Figure 2) is a tube A with the conifuge K, and the flow rate in this instrument can be varied with the spray head D from 10 to 25 meters/second and the collector device 3. Sampling is carried out in a tube with cross-sectional radius of 2 mm and a mean curvature of 6 mm on the plate P, the surface of which is a section of the internal tube surface. The orifice of the tube is covered the curtain C with an automatic device that permits making plate exposures of different durations. The flow rate in the tube can be regulated by the gauge B from 0 to 70 meters/second.

Samples of an artificial cloud produced in an 11 m^3 chamber and samples of natural aerosols are collected on a plate coated with a mixture of transformer oil and vaseline. Simultaneously aerosol samples were collected by a flow collector built in the Elbrus expedition of the Academy of Sciences USSR. After photographing with a biological microscope with a "Zenith-S" chamber, the number of drops and the dimensions of each were determined by a counting device that consisted of telephonic counters and a switchboard distributing block.

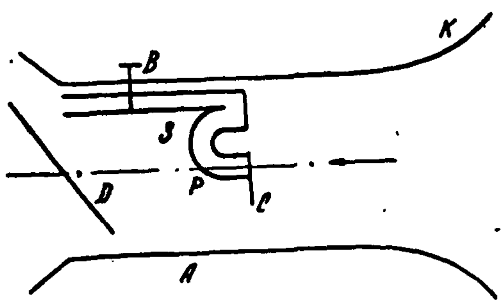


Figure 2.

Analysis of the results was done as follows. The plate exposed in the cloud was photographed under the microscope at several places, and the position of the center of each frame was determined on the scale of the sample leader. After the film was developed, the number and size of each drop were determined with the counting device. To determine the scale of images on the film, the scale of the objective-microscope was photographed. To check the applicability of the logarithmically normal law, on the abscissa axis was plotted the logarithm

of the drop diameter, and on the ordinate axis -- $y = \Phi^{-1}[H(d)]$, where $H(d)$ = relative number of drops in the sample with diameter less than d, Φ^{-1} = function that is the reciprocal of the normalizing function of normal distribution. The results of analyzing one of the sample using this method are presented in the table and in Figure 3. The rows 1-9 in Figure 3 are the results of analyzing individual frames. Data obtained as a result of analyzing the entire sample is plotted as a heavy line. It must be noted that in individual frames and in the entire plate the distributions are close to the logarithmically normal. The results of analyzing the sample collected simultaneously by the collector of the Elbrus expedition after calculation of the capture coefficient E(d) are shown in Figure 4. An approximation suggested by L. M. Levin [1] was used as the capture coefficient:

$$\frac{1}{E} = 1 + \frac{70}{d_\mu^2}. \tag{9}$$

In this form, (9) can be used for the flow rate in the collector v = 15 meters/second and for the parameters of the collector plate used in the studies of the Elbrus expedition.

From a comparison of Figures 3 and 4, it is clear that the values of the median diameters for samples taken by the flow collector have been obtained overstated. This circumstance, in particular, can be explained as follows. The aspiration coefficient in the tube, as was shown in [1] depends substantially on the amount of air intake through it and on the velocity and direction of the wind. No distortions in the case of isokinetic conditions of sampling are introduced into the flow of the aerosol through the tube. To satisfy these conditions, the velocity of the air flow within the tube must equal the velocity of the external flow parallel to which the tube is oriented, and the thickness of the tube wall can be neglected. In our experiments, for velocities up to 25 meters/second the conditions of sampling by the collector were close to the isokinetic; for velocities higher than 25 meters/second, the flow concentration of large drops in the sample collected is reduced, which can explain to some extent the above-indicated discrepancy.

Essential to the collection of samples in the tube is the condition of flow laminarity. In the tube of the collector the Re number for the highest flow rates does not exceed 10^3. For a rigorous solution of the problem, it is necessary to estimate the effect of the boundary layer on the critical value of the Stokes number k_{cr} and the effect of turbulent settling in the boundary region. These questions will be the subject of further exploration.

The recorded minimum drop diameter is 0.8 μ. No drops at all were observed at the end of the plate. This fact can be explained by the coefficient of settling for drops of all diameters, up to d = 0.8, being close to unity. The estimate of S_i for drops of minimum diameters

made with the aid of (7) gives close values for the distance S_i of these drops on the collector plate.

TABLE

(a) № кадра				(a) № кадра														
μ	1		μ	2		3		4		5		6		7		8		
	h_i	$H(d)$		h_i	$H(d)$	h_i	$H(d)$	h_i	$H(d)$	h_i	$H(d)$	h_i	$H(d)$	h_i	$H(d)$	h_i	$H(d)$	
5,7	14	7	3,1	7	1,9	7	2,0	11	3,3	78	17.8	76	24,3	69	30,1	44	54.6	
9,6	35	24	5,2	75	22	95	28,9	134	43,9	184	59,9	141	69.3	125	84,9	37	100	
12,0	37	42	7,3	93	47,7	108	59,5	120	81,1	122	87 8	74	92,9	31	98,1	—	—	
15,4	29	56	9,5	69	72,2	106	89 6	48	94,6	46	98,3	19	99.0	4	99 9	—	—	
21,0	46	79	11.5	51	86,3	25	96,7	17	99,7	7	99,9	3	100	—	—	—	—	
24,8	24	91	13,7	26	93 5	9	90,2	—	—	—	—	—	—	—	—	—	—	
28,6	9	95,6	15,7	20	99,0	3	100	—	—	—	—	—	—	—	—	—	—	
32 5	6	98 5	17,8	2	99,5	—	—	—	—	—	—	—	—	—	—	—	—	
36,3	3	99,9	20.0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	

LEGEND: a) cadre number.

Figure 5 is the median diameter for the size distribution function of particles on an individual frame as a function of distance l on the collector plate. The points represent experimental results. The solid curve stands for the graph of the function ld_m = const. Deviations of experimental points from the curve lie within the limits of measurement error. The good conformity of the ratio ld_m = const evidences that the flow is sufficiently laminar and that neglect of the correction ΔS is graduation of the collector is justified.

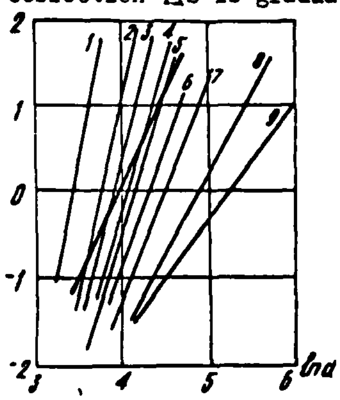


Figure 3

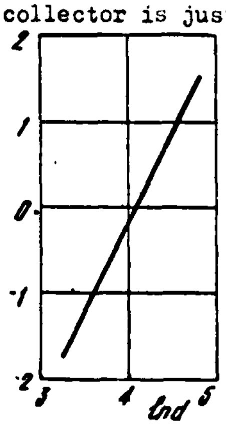
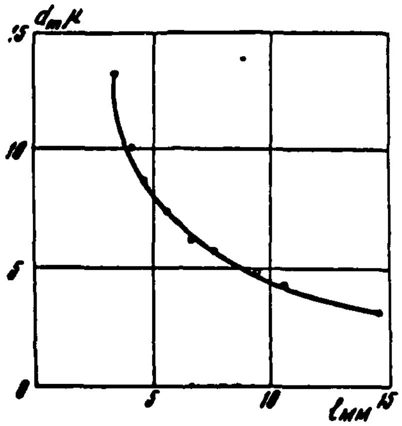


Figure 4

IV. To graduate the collector, it is necessary to obtain a

graph sim'lar to tha shown in Figure 5. At a given flow rate $\bar{u}$ in the collector and constant characteristics of the collecting instrument, the graduation graph will be rigorous in contrast to graphs given in [5]. After a graduating curve is obtained, the boundaries of counting sections are determined with account taken of the presumed microstructure of the investigated aerosol, exposure in collecting the sample, and the effect of fluctuations of the number of particles in the volume taken [1, 2]. The size of the sections must be estimated to obtain statistically determinate results. The last stage must be the counting of the number of drops on each section of the collector plate. Using the graph in Figure 5, we find the values of the diameters of the drops falling within the boundaries of the sections, after which the rectified cumulative diagram for the given distribution is plotted. The method of analyzing the results that has been described can be used for samples, the particle sizes in which are distributed according to any law.

Figure 5



The proposed method, not introducing significant errors as a result of measurements, affords a simplification and acceleration of the obtaining of information on the microstructure of an aerosol. This is accounted for by the fact that in determining parameters of size-distribution functions of particles completely excludes microphotographing and determination of the dimensions of the image of each drop. The microphotography method is used only in graduating a collector, which must be done extremely carefully. By measuring the geometry of the collector tube and the coating of the collector plate, we can investigate particles in mists and large and giant condensation nuclei in the open atmosphere.

In conclusion, I regard it as my happy duty to express my gratitude to V. Ye. Zuyev for his manifold assistance in conducting this study.

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